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Method for determination of the state of ageing of a battery

It is known for a battery to be monitored to determine how much charge can still be drawn from it in a respective charging cycle. A method is also known in which simulated battery operation is carried out on a computer-aided basis in parallel with the battery operation. Battery state variables are checked from the simulation model, for example a statement about the battery age.

A method is proposed for determining the state of ageing of a battery, in which a battery ageing characteristic is predetermined empirically, with the discharge amount per discharge cycle being used as the input variable which is identified as being relevant to battery ageing. Ageing components for the respective instantaneous battery state are determined on the basis

of the predetermined characteristic and continuous measured-value monitoring on the battery, and the battery ageing is determined by addition of the determined ageing components. It has been found that, with a comparatively simple implementation, this method takes account of the most important influencing variables that are relevant to ageing, in an adequate manner for reliable determination of the state of ageing of the battery.

Use, for example, for determination of the remaining life of traction batteries in electrical vehicles or for determination of the remaining rated capacity, that is to say range.

Description

The invention relates to a method for determination of the state of ageing of a battery. A method such as this is used, for example, for traction batteries in electrical vehicles, since it is important for the operator of an electrical vehicle to be informed of the state of ageing, and thus of the presumptive remaining life of the traction battery. Traction batteries in electrical vehicles are subject to severe loads and have only a limited life in the sense that, as the period of use increases, the amount of charge which can be stored falls until the battery can no longer be used for driving. With knowledge of the state of ageing of the traction battery, the possible vehicle range can be estimated, and a nominal function can be created for a battery such as this, in such a way that discrepancies from this during operation indicate a battery defect, which can be indicated to the driver via an appropriate display appliance. Other driver information, such as the request for a charging reset, that is to say for charging of the battery, as is expedient after a number of partial discharge cycles for calibration of the state of charge indication, can also be produced if the battery age is known with better accuracy. The mechanisms which lead to ageing of batteries differ widely. Major effects which may be stated are the adverse effect on the ion exchange as a result of dirt or other deactivation of the contact surfaces of the reactants or of the electrolyte or ion transmitter, as well as the deactivation of a part of the chemical reaction compound as a result of undesirable chemical secondary reactions or as a result of the formation of isolating intermediate layers. Which effects dominate depend not only on the chemicals that are used but also on the geometric form and the technology of the battery manufacturer, with certain major influences being common to all systems, for example the ageing dependency of the amount of charge which is drawn from

the battery per discharge cycle, and the respective remaining amount of charge which is still stored.

A large number of methods are known for determination of the state of charge of a battery within a discharge cycle, for example by measurement of the battery voltage on load, or by recording the previous discharge duration after a charging process. By way of example, the patent specification US 4,743,831, US 5,065,084 and US 4,017,724 as well as the Laid-Open Specifications DE 41 12 987 A1 and DE 42 21 513 A1 may be cited as being representative of these methods. In contrast, these methods are not intended to make any statement about the state of ageing of the battery.

Patent Specification DE 40 14 737 C2 describes a method for determination of the state of charge and of further physical variables for a battery, in which, inter alia, it is also possible to provide for ageing information to be obtained. The method is based on the principle of carrying out a model-based simulation in parallel with the actual battery processes, to which simulation the same process input variables are supplied as in the case of the real process. The simulation uses a model with a range of parameters. After each process cycle, the values which are measured in the real process are compared with the values measured from the simulation, and the model parameters are adapted as a function of this, in the sense of minimizing the discrepancy between the real and the modeled process output variables. By way of example, process input variables include the current level, the time as well as the battery temperature and the ambient temperature, while for example, the time profile of the battery voltage represents a process output variable.

Laid-Open Specification DE 34 29 145 A1 discloses a

method for determination of the state of charge of a rechargeable battery by calculation of the total battery capacity by means of the so-called Peukert equation, and integration of the battery current over time, and calculation of the percentage component of the battery capacity that has not yet been used. In this case, the respective battery age is required as an input variable for the Peukert equation and a determination is made in such a way that an incremental age counter is repeatedly incremented in steps whenever a complete discharge cycle from a state of charge of more than 80% of the maximum state of charge to a state of charge below 40% thereof, has been found.

The technical problem on which the invention is based is to provide a method for determination of the battery state of ageing which can be carried out comparatively easily and allows a relatively reliable estimate of the remaining life of a battery.

This problem is solved by a method having the features of Patent Claim 1. The method is based on the knowledge that the overall life of a battery depends mainly on one or a small number of battery ageing influencing variables, one of these being the amount of discharge, that is to say the amount of charge drawn from the battery, per discharge cycle. This is because it has been found that the battery life depends significantly on the amount of charge which is in each case drawn per discharge cycle over the course of its operating life. First of all, a family of characteristics can be produced empirically on the basis of a deterministic model of the battery life as a function of this and, possibly, of further variables which have been identified as being relevant, which family of characteristics indicates for each set of influencing variable values how long the battery could be operated

for in these conditions with a given statistical probability or, in other words, what amount of charge, expressed for example in units of the battery rated capacity, could then be drawn in total from the battery over the course of its life. By continuously determining the values for the influencing variables throughout the use of the battery, an estimate of the battery state of ageing can be obtained directly on the basis of the family of characteristics in a manner which can be carried out with comparatively little effort.

In this case, an ageing component is determined for each discharge or charging cycle as a function of the respective set of influencing variable values on the basis of the family of characteristics, which mainly includes the fraction which the respective cycle represents of the battery life stored in the family of characteristics in the corresponding conditions. The respective battery state of ageing is then determined as the sum of these ageing components. It has been found that the assumption made in the ageing influences of the individual discharge and charging cycles having an additive behavior makes the method highly practical and leads to plausible estimates of the battery life. Furthermore, over the course of its use, the method can lead to continually better accuracy as a result of the fact that the family of characteristics which represents the empirical data is in each case updated with the results obtained on the present battery system.

In a refinement of the invention as claimed in claim 2, the battery life to be expected for a respective set of influencing variable values is defined, for the production of the family of characteristics, by the time period from which, statistically on average, a

predetermined percentage of monitored batteries of the respective type would no longer achieve a predetermined performance value.

In a development of the invention as claimed in claim 3, the discharge depth in each case reached during each discharge cycle is also taken into account as a battery ageing influencing variable, in addition to the amount of discharging per discharge cycle. It has been found that this leads to an improvement in accuracy since battery ageing depends not only on the respective amount of discharging, but also on the amount of charge that is still present in the battery at the end of a discharge cycle.

Further accuracy improvements can be achieved by additionally taking account of an ageing factor which is dependent on the remaining life and/or an ageing factor which takes account of vibration, as claimed in claim 4.

In a development of the invention as claimed in claim 5, the ageing value is assumed to be additively composed of an ageing value which is dependent on operation and an ageing value which is dependent on storage, that is to say takes account of the time period since manufacture of the battery, so that the model on which the method is based also takes account of the ageing of the battery that is independent of its operation. A further refinement, as claimed in claim 6, takes account of the fact that the respective battery state of the charge affects the ageing which is dependent on storage.

Increased accuracy in the determination of age can furthermore be achieved by a development of the invention as claimed in claim 7, in which the so-called

memory effect and/or the temperature dependence of battery ageing are/is taken into account.

In the same way, as claimed in claim 8, it is also possible to take account of ageing effects which result from chemical secondary reactions, such as those which are known from overcharging, deep discharging or, possibly, polarity reversal. Furthermore, as is claimed in claim 9, the ageing which has already occurred can be taken into account in that all the other amounts of charge that are drawn are related, in terms of their damaging effect, to the remaining residual capacity or residual performance.

In one advantageous refinement of the invention, as claimed in claim 10, the state of ageing of the battery is stored in a non-volatile memory, from which an on-board computer can take data in order to calculate the remaining battery range. If required, as claimed in claim 11, a warning signal or fault signal can additionally be emitted by the on-board computer in the event of a discrepancy between the battery operating point and its rated operating point on the basis of ageing.

Preferred embodiments of the invention will be explained in more detail in the following text in conjunction with the drawings which illustrate them, and in which:

Figure 1 shows an illustration of the functional relationship between the maximum amount of charge which can be drawn during a discharge cycle, as a function of the total amount of charge which has been drawn over the previous life, for various amounts of discharge per discharge cycle for typical vehicle traction batteries,

Figure 2 shows an illustration of the life curve which results from Figure 1 in the form of a graph of the amount of discharge per discharge cycle and the total amount of charge drawn from the battery,

Figure 3 shows a typical detail from the time profile of the battery current level and the stored battery charge during battery operation,

Figure 4 shows an illustration, in the form of a graph, of the frequency of amounts of charge drawn and stored per charging and discharge cycle in the time period shown in Figure 3,

Figure 5 shows an illustration in the form of a graph of the discharge amounts in various charging classes in the cycle time period in Figure 3,

Figure 6 shows two illustrations in the form of graphs and one illustration in the form of a table of a further typical detail from the time profile of battery operation with discharge classification,

Figure 7 shows an illustration, in the form of a graph, of life curves in the form of a diagram of the remaining amount of charge and the total amount of charge drawn,

Figure 8 shows an illustration, in the form of a graph, of the functional relationship of an ageing factor which is dependent on storage and the state of charge,

Figure 9 shows an illustration, in the form of a graph, of the functional relationship between a self-reinforcing ageing factor and the battery life, and

Figure 10 shows an illustration, in the form of a

graph, of the functional relationship between a vibration-dependent ageing factor and the vibration acceleration.

The invention is based on the discovery that the amount of charge which can be drawn in total from a battery over the course of its life before it has deteriorated by ageing to such an extent that it can no longer be used to store a specific minimum amount of charge depends in a significant manner on the amount of charge which is drawn from the battery per discharge cycle. It has been found that the battery ages more quickly, that is to say the total amount of charge which can be drawn during its life becomes less, the greater the amount of charge which is drawn per discharge cycle. This relationship is illustrated in Figures 1 and 2.

Figure 1 shows the relationship between the maximum amount of capacity (EK) which can be drawn during each discharge cycle, that is to say the respective maximum amount of charge which can be stored in the battery, and the rated capacity (N) and the battery state of ageing, represented by the total amount of charge which has already been drawn over the battery life divided by its rated capacity when in the new state, indicated as the number of rated capacity units (NK) which have been passed through. Figure 1 shows three curve profiles which illustrate the functional relationship between the above variables for various values of the amount of charge (EM) drawn per discharge cycle related to the respective maximum capacity of a fully charged battery. The illustrated curves are applicable in an idealized form to a battery which is in each case discharged by the respectively selected amount of discharge (EM) from the fully charged state, and is then charged again, during its life. The left-hand curve relates to a situation in which the battery is always entirely

discharged, that is to say EM = 100%, the central curve relates to the situation where the battery is in each case half-discharged, that is to say EM = 50%, and the right-curve relates to the situation in which only 10% of the amount of charge added to it is drawn from the battery in each case, that is to say EM = 10%. In all three cases, the amount of charge which can be drawn is initially somewhat greater than the rated capacity in the new state, that is to say EK = 100%, and then falls continuously as battery operation continues further. As soon as only an amount of charge which is less than a predetermined limit value can still be stored in the battery, this is defined as the end of use and thus the maximum battery age. In Figure 1, this end of use limit value is chosen to be 80% of the rated capacity, illustrated by the associated horizontal end of use line (GE) which is below the rated capacity line (NL) by the appropriately preselected interval. The respective intersection (a, b, c) of the three curves in Figure 1 with the end of use line (GE) in consequence represents the respective end of use of a correspondingly discharged battery although, as can be seen, considerably different battery ages (NK_a, NK_b, NK_c), that is to say amounts of charge which can be drawn in total over the life of the battery, are evident. It has been found that the total amount of charge which can be drawn falls as the amount of charge discharged per discharge cycle increases, with the total amount of charge which can be drawn being between 500 times and 2000 times the battery rated capacity, depending on the type.

This relationship is illustrated in Figure 2 where the amount of charge (EM) which is drawn per discharge cycle is shown, once again as a percentage of the rated capacity (N) over the number of rated capacity units (NK) passed through, that is to say the total amount of

charge drawn in units of the rated capacity. The diagram which results from these two variables shows the life line (LD), which in consequence indicates the total number of rated capacity units (NK) which can be passed through for a specific value of the amount of charge (EM) drawn per discharge cycle. In consequence, inter alia, the three intersections (a, b, c) shown in Figure 1 are located on this line LD. The falling profile of the life line (LD) reflects the fact which has been mentioned of more rapid ageing as the amount of charge (EM) drawn per discharge cycle becomes greater. Subject to the precondition that the battery is in each case completely recharged before the start of a discharge cycle, the amount of charge (EM) drawn in general corresponds to the so-called discharge depth (ET) when the latter is defined as the difference between the amount of charge in each case stored in a fully charged battery and the amount of charge which is still present at the end of a discharge cycle. If the amount of discharge (EM) is constant, the total number of discharge cycles which can be carried out with the battery can easily be calculated from the respectively determined maximum number of rated capacity units which can be passed through, as the quotient of the maximum number of rated capacity units which can be passed through divided by the amount of discharge (EM) per cycle. If, for example, the central curve in Figure 1 is considered, that is to say a battery which is in each case half-discharged, that is to say EM = 0.5, the number of charging units (NK_b) which can be passed through before the end of use is 1100, that is to say NK_b = 1100, so that 2200 discharge cycles can be carried out with the battery before the end of use.

This discovery, which has been described above, relating to the fact that the battery ageing is dependent on the amount of discharge is now used as the

model basis for the actual battery ageing determination process described in the following text. In this case, it should also be mentioned that the above ageing principle takes place in all battery systems. As the basis for the ageing determination model, which uses characteristics of the type illustrated in Figure 2, investigations were carried out with a respective set of batteries, in which each of the parameters included in the model, such as the amount of discharge per discharge cycle (EM) was varied and the measurement data was evaluated statistically until the mathematical relationships assumed for the model were sufficiently reliable for ageing determination. By way of example, it can be stated that the method is useable when a specific percentage, for example 90%, of all the batteries monitored at the time which is defined as the end of use by the method, are still operable, since the method then in each case provides a highly reliable estimate of the decrease in the battery age.

The starting point for carrying out the method is thus first of all a family of characteristics for the empirically determined battery ageing as a function of the battery ageing influencing variables which are regarded as being relevant, indicating the battery life to be expected statistically for each set of influencing variable values when the battery is always operated in an idealized manner in conditions which correspond to these values. Starting from this point, the method can now comprise the detection of the relevant battery ageing influencing variables during battery operation, with each occurrence of a specific set of influencing variable values being associated with an ageing component, and these ageing components being added up. When the sum has exceeded a specific value, the value unity in normalized units, then this is interpreted as the statistical end of use of the

battery which, for example, can be defined in the family of characteristics in that a predetermined percentage, for example 90%, of the tested batteries no longer reach the specific performance values, for example various electrical characteristics such as the amount of charge which can be stored, during the empirical series of trials. It is thus assumed that the various ageing influences can be broken down into independent, additive components, which has been found in practice to provide a very useful approximation. Each of the ageing components is determined as the component of the operating cycle, which is characterized by the respective set of influencing variable values, for the life to be expected, which is stored for this value set in the family of characteristics. The amount of discharge per discharge cycle is in each case used as an influencing variable in this case, in order to take account of its influence on battery ageing, which can be seen from Figures 1 and 2. In addition, depending on the desired accuracy and the available effort, further influencing variables may be taken into account, to the extent that their influence on battery ageing is known and can be stored quantitatively in the form of the family of characteristics.

A method example of this type which can be carried out with little effort, as well as possible modifications to it, will be described in more detail in the following text

As a first approximation, the plausible assumption is made that the ageing of the battery which results from storage is independent of the battery ageing which results from operation. This leads to a remaining life to be expected (LR) normalized with respect to unity, in the form

$$L_R = 1 - A_B - A_L$$

where A_B is the ageing dependent on operation and A_L is the ageing of the battery dependent on storage. To first approximation, the ageing (A_L) which is dependent on storage can be expressed by:

$$A_L = t/T_M$$

where t is the time of its manufacture or initial activation by acid filling, and T_M is the maximum battery life without any discharge and charging cycles.

In order to determine the battery ageing (A_B) which is dependent on operation, it is assumed to a first approximation that the associated ageing mechanism includes only the discharge processes and not the charging processes, to be precise initially only as a function of the respective amount of charge (EM) drawn, irrespective of the charge level of the battery at the end of a partial discharge. This assumption is not unrealistic since a large number of battery types indicate a dependency of ageing as a function of the state of charge only in the vicinity of deep discharging. However, this operating rate is generally avoided by the battery controller. Accordingly, in accordance with the method, the amounts of charge drawn (EM) in successive discharge cycles are recorded by continuous battery current monitoring throughout the course of battery operation. Figure 3 shows a detail from such monitoring in the form of a diagram, to be precise with the upper diagram showing the current level (I) as a function of the time (t), and the lower diagram showing the charge (Q) stored in the battery in the same time period. Each zero crossing (t_1 to t_9) of the current level/time curve illustrated indicates the

end of a discharge cycle, if the curve has previously fallen below the abscissa, or a charging cycle, if the curve has previously been above the abscissa. Integration of the curve for each cycle results in the respective amount of charge drawn during discharging of the battery (Q_1, Q_3, Q_5, Q_7, Q_9) or the amount of charge stored while it is being charged (Q_2, Q_4, Q_6, Q_8). The lower diagram shows the associated time profile of the amount of charge (Q) in each case stored in the battery when the battery is initially charged with its full rated charge (Q_{rated}). Table 1, below, shows the values obtained for the operating detail from Figure 3 for the amounts of charge used in the nine cycles, with positive values denoting stored amounts of charge and negative values denoting amounts of charge drawn, in each case as a percentage of the battery rated capacity.

Table 1

Cycle i	1	2	3	4	5	6	7	8	9
Q_i	-49	+16	-38	+32	-8	+12	-11	+15	-12

The ageing component (A_B) which is dependent on operation is obtained from the sum of the individual ageing components for each discharge cycle. The component for each discharge cycle is in this case found by using the empirically determined, stored life characteristic (LD), as illustrated in Figure 2, to look for the value, associated with the amount of charge drawn (EM) recorded for this cycle, of the maximum number (NK) of charge units which can be passed through for this amount of discharge, and dividing the amount of discharge (EM), normalized with respect to the rated capacity, by this value. As a practical simplification, the amount of discharge range can be subdivided from 0% to 100% into intervals, for example

each having a length of 10%, with each discharge cycle being associated with one of these intervals on the basis of its amount of discharge. In order to determine the battery ageing resulting from operation so far, the frequency of discharge cycles included is multiplied for each interval by the mean value of the amount of discharge in the interval and is divided by the maximum number (NK) of charging units which can be passed through associated with the interval mean value, with the ageing components determined in this way in each interval then being added up.

The use of this ageing component calculation for the operating section shown in Figure 3 will be described in order to illustrate this. First of all, Figure 4 shows the frequency (N_{charge}) of the charging and discharge cycles shown in Table 1 in the form of a histogram, with the amounts of charge being classified in intervals each having a length of 10% of the rated charge. The Q_+ half-axis in this case indicates the charging cycles, and the Q_- half-axis indicates the discharge cycles. If only the discharge processes are considered in the histogram shown in Figure 4, and the frequency (N_{charge}) of each interval is multiplied by the mean value of its amount of charge, then this results in the illustration shown in Figure 5, which shows the total amount of charge (N_K) drawn per discharge interval, in the form of a histogram as a respective fraction of the rated capacity. As can be seen from Table 1 and Figure 4, there is one discharge cycle in the amount of discharge interval from 0% to 10%, but two cycles in the interval from 11% to 20%, and there is in each case one cycle again in each of the intervals from 31% to 40% and from 41% to 50%. With the values given by the life line (LD), the maximum of charging units which can be passed through (NK(5%)= 1700, NK(15%) = 1530, NK(35%) = 1260 and

NK(45%) = 1150 for the drawing interval mean values 5%, 15%, 35% and 45%, resulting in the following expression for the total ageing component, which is dependent on operation, in this operating section:

$$A_s = 1 \cdot \frac{0.05}{1700} + 2 \cdot \frac{0.15}{1530} + 1 \cdot \frac{0.35}{1260} + 1 \cdot \frac{0.45}{1150} \approx 0.00089 .$$

In consequence, the battery has aged through 0.089% of its total operating life during this operating phase. By definition, the end of use of the battery is not reached until the sum of all the ageing components has reached the value unity, in that there is then a 90% probability that only 80% of its rated capacity can still be drawn. It is self-evident that, in addition to the remaining life defined in this way, with, for example, the empirically determined knowledge of the dependency of the battery storage capacity, it is also possible to determine the respective instantaneous maximum discharge capability, that is to say the maximum amount of charge which can still be stored in the battery. This value can also be included in a state of charge and range indication for the traction battery for the electrical vehicle, in the same way as the remaining life value.

In order to improve the accuracy, the algorithm described above can be used to additively take account of the ageing dependency of the discharge depth, that is to say the difference between the instantaneous battery capacity and a remaining amount of charge (RL) which is in each case still stored after a discharge cycle, in a simple manner, as follows. Instead of the life line (LD) shown in Figure 2, a two-dimensional family of life characteristics is used, which is likewise once again determined empirically and of which Figure 7 shows the relationship between the life, expressed in the maximum number (NK) of rated capacity

units which are passed through, and remaining charge (RL) after each discharge cycle, indicated as a percentage of the rated capacity (N) for four discharge amount intervals, with the first curve (LL_1) being associated with the discharge amount interval from 91% to 100%, the second (LL_2) being associated with the interval between 41% and 50%, the third (LL_3) being associated with the interval between 11% and 20%, and the fourth curve (LL_4) being associated with the interval between 0% and 10% of the battery capacity. As can be seen from this figure, if the amount of discharge per cycle is constant, the battery life decreases as the discharge depth increases, so that the remaining amount of charge (RL) thus falls at the same time, in particular in the event of a deep discharge depth and thus with a small remaining amount of charge (RL), thus reflecting the sensitivity of this type of battery to deep discharges.

In this case, the component of ageing which is dependent on operation is determined by monitoring the battery current and the stored, two-parameter family characteristics, by determining the associated parameter pair, comprising the amount of discharge (EM) and the remaining amount of charge (RL) for each discharge cycle, and by determining the reciprocal of the associated maximum number of charging units (NK) which can be passed through, and multiplying this by the associated amount of discharge (EM).

Once again, the method can in practice be simplified by also subdividing the range of the amount of remaining charge (RL) into intervals with a length of, for example, 10%, and by associating a predetermined interval pair with each discharge cycle. Figure 6 illustrates one example relating to this. The uppermost diagram in Figure 6 shows the profile of the battery

current level (I) as a function of the time (t) within a selected section of the battery operation, analogously to the upper diagram in Figure 3. In this case, discharge cycles and charging cycles in each case occur alternately, with the respective amount of charge passed through being stated as a percentage of the rated charge (Q_{rated}). The last two discharge cycles, each with a discharge amount of 15%, are combined to form a single discharge cycle with a 30% discharge amount, since there is no charging cycle between them. Once again corresponding to Figure 3, the diagram below this shows the charge (Q) which is in each case still stored in the battery in the same time period, starting from a fully charged battery. The percentages quoted along the charging curve in each case represent the discharge depth, that is to say the difference between the rated charge (Q_{rated}) and the instantaneous battery charge (Q) at the end of a respective discharge cycle or charging cycle. The table below this in Figure 6 indicates in a tabular form the charging interval classification for the individual discharge amount intervals (j) and discharge depth interval (i), with the four discharge cycles in the time period selected in the diagrams above this being entered in the table field, with their frequency. In order to determine the respective instantaneous ageing which is dependent on operation, the components of all the interval pairs (I_i, I_j) are then added up, which in each case result once again from the frequency of associated discharge cycles multiplied by the associated mean value of the discharge amount interval, and divided by the associated maximum number of charging units which can be passed through, so that the ageing (A_B) which is dependent on operation can be written in the form:

$$A_B = \sum_{i,j} A_{i,j}$$

where $A_{i,j}$ represents the component of one interval pair. As an example, the operating phase shown in Figure 3 results, when using this method variant, in a discharge cycle in each case occuring once for the interval pairs 0% to 10% discharge amount and 41% to 50% remaining charge amount, 31% to 40% discharge amount and 21% to 30% remaining charge amount, as well as a 41% to 50% discharge amount and 51% to 60% remaining charge amount, as well as a double occurrence of the interval pair with an 11% to 20% discharge amount and 51% to 60% remaining charge amount, subject to the precondition that the battery is fully charged at the starting time.

Depending on the application, further method variants may be considered in order to improve the accuracy. For example, the above algorithm can be extended appropriately to charging cycles when the charging of the battery is also relevant to the battery ageing mechanism. In the case of batteries with a memory effect, for example NiCd batteries, which are first discharged before being fully charged for normalization purposes, a modification of the method is expedient, in which the above ageing components ($A_{i,j}$) of the discharge interval pairs are added up within a normalization interval, and these intermediate sums are provided with special coefficients (Φ_k), before they then added up to form the overall sum using:

$$A_s = \sum_k \sum_{i,j} A_{i,j} \cdot \phi_k$$

If required, the rate of charging or discharging can also be taken into account, if the thermal loads which result from this are compensated for only incompletely by cooling systems. Coefficients formed for this purpose can best be recorded empirically by measuring the temperature discrepancy relative to the rest

temperature. Since the thermal load is associated with the respective charging cycle or discharge cycle (in the case of lead-acid batteries, only for the charging process since their temperature is constant during discharging), the temperature influence is in this case associated directly, as the coefficient (ϕ_t), with the interval pair ageing component ($A_{i,j}$) for the respective time (t), that is to say:

$$A_B = \sum_t \sum_{i,j} A_{i,j} \cdot \varphi_t \, .$$

If it is found that the ageing which is dependent on storage depends on the state of charge of the battery, this can be taken into account by means of a charging coefficient (λ), which is associated with a respective state of charge, so that this modified ageing component (A_L) becomes:

$$A_L = \sum_k t_k \cdot \lambda_k / T_K$$

(see the definition form on page 11 of the original German text). By way of example, Figure 8 shows one such relationship between the charging coefficient (λ) and the state of charge, that is to say the remaining amount of charge (RL), for one specific battery type. In this case, the charging coefficient (λ) represents a non-dimensional damage factor, for example a battery which has been deeply discharged ages considerably more quickly than a full battery.

If the battery is of a type which has a self-reinforcing ageing influence, for example by partial deactivation as a result of secondary reactions and a higher load (associated with this) on the remaining reaction mass, this can be taken into account by means of a further parameter (τ). Figure 9 shows a typical profile of this ageing reinforcement factor (τ) as a function of the respective instantaneous, normalized

remaining life (RL). This factor (τ) in this case affects not only the ageing component which is dependent on operation but also the ageing component which is dependent on storage.

Furthermore, if required, battery ageing caused by mechanical vibration can be taken into account in a similar manner. Figure 10 shows one typical relationship such as this between a vibration ageing coefficient (σ) and the mean vibration acceleration (a), normalized with respect to the acceleration due to gravity, related to vibration at 15 Hz. This ageing factor also influences both the ageing component which is dependent on operation and the ageing component which is dependent on storage.

It is evident from the above description of preferred method variants that the present method allows very accurate determination of the state of ageing and thus of the remaining life to be expected from a battery which is in operation, for example a traction battery in an electrical vehicle, with comparatively little measurement and computation complexity, using empirically determined characteristic data and an algorithm which is simple to handle, in each case including the influencing variables which have been identified as being relevant for battery ageing.

In order to allow the remaining range of the traction battery to be calculated, the respectively determined state of ageing of the battery is stored in a non-volatile memory in the system which is carrying out the method. An on-board computer can then take data from this memory, which it requires in order to calculate the respective remaining rated capacity, and thus the remaining range of the battery. In addition, the on-board computer can take data from the non-volatile

memory in order to make it possible to detect any discrepancy between the battery operating point and the rated operating point on the basis of ageing, in response to which it emits a warning or fault signal.

Patent Claims

1. A method for determination of the state of ageing of a battery, comprising the following steps:

- predetermination of a family of characteristics for battery ageing as a function of a group of battery ageing influencing variables which includes at least the variable of the amount of discharge per discharge cycle (EM),
- recording of the respective instantaneous values of the battery ageing influencing variables for the monitored battery, and determination of the ageing component which is associated with these respective instantaneous values of the influencing variables, on the basis of the predetermined family of characteristics, as well as
- addition of the determined ageing components in order to form a battery ageing value as a measure of the battery state of ageing.

2. The method as claimed in claim 1, wherein, furthermore, the end of use of the battery is defined as a normalized battery ageing value reaching the value unity, which value is normalized with respect to a life from which a predetermined percentage investigated empirically in order to predetermine the family of characteristics, the battery no longer reaches the predetermined performance values.

3. The method as claimed in claim 1 or 2, wherein, furthermore, the remaining amount of charge (RL) which is present after a respective discharge cycle is taken into account as the battery ageing influencing variable.

4. The method as claimed in one of claims 1 to 3, wherein, furthermore, an ageing factor (τ, σ), which is

dependent on the remaining life (L_R) and/or an ageing factor (τ, σ) which is dependent on vibration (a) are/is taken into account as a battery ageing influencing variable or variables.

5. The method as claimed in one of claims 1 to 4, wherein, furthermore, the battery ageing value is additively composed of an ageing value (A_B) which is dependent on operation and an ageing value (A_L) which is dependent on storage.

6. The method as claimed in claim 5, wherein, furthermore, the respective battery state of charge (RL) is included as a battery ageing influencing variable in the storage-dependent ageing component, in the form of a factor (λ).

7. The method as claimed in one of claims 1 to 6, wherein, furthermore, the battery memory effect and/or the battery temperature are/is included in the ageing component which is dependent on operation, as battery ageing influencing variables in the form of a respective factor (Φ,Ψ).

8. The method as claimed in one of claims 1 to 7, wherein, furthermore, chemical secondary reactions which adversely affect the capacity or performance of the battery are assessed as an ageing component.

9. The method as claimed in one of claims 1 to 8, wherein, furthermore, the ageing which has already occurred is taken into account in such a way that all of the further amounts of charge drawn are related in terms of their damaging effect to the remaining residual capacity or residual performance.

10. The method as claimed in one of claims 1 to 9,

wherein, furthermore, ageing state data for the battery is stored in a non-volatile memory, in which case the data can be read by an on-board computer and can be evaluated in order to calculate the remaining battery range.

11. The method as claimed in one of claims 1 to 11, wherein, furthermore, ageing state data for the battery is stored in a non-volatile memory which can be read by an on-board computer and can be evaluated in order to define any discrepancy between the battery operating point and its rated operated point on the basis of ageing, with the on-board computer emitting a warning or fault signal when it identifies a discrepancy.

5 pages of drawings attached

Number: DE 195 40 827 A1
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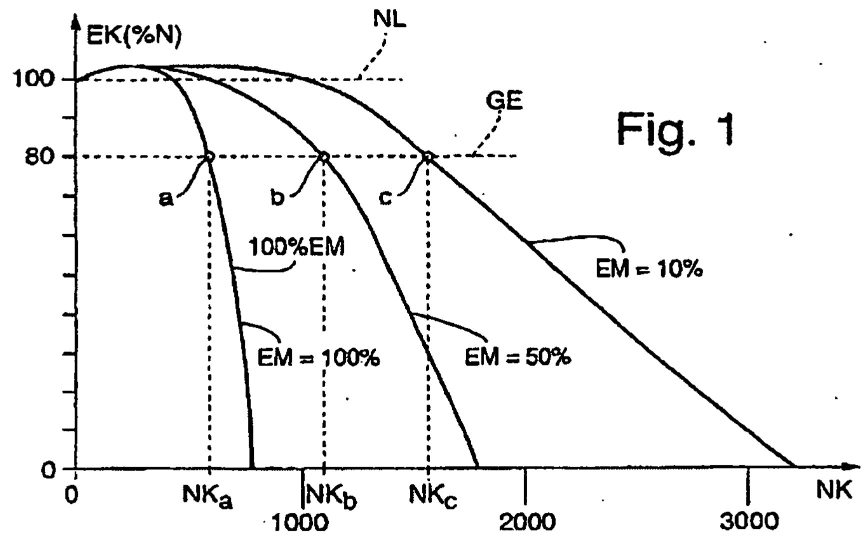


Fig. 1

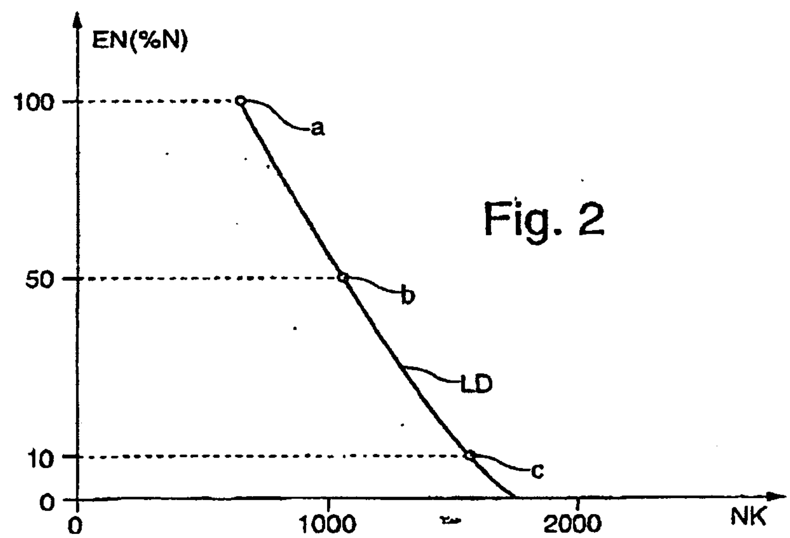
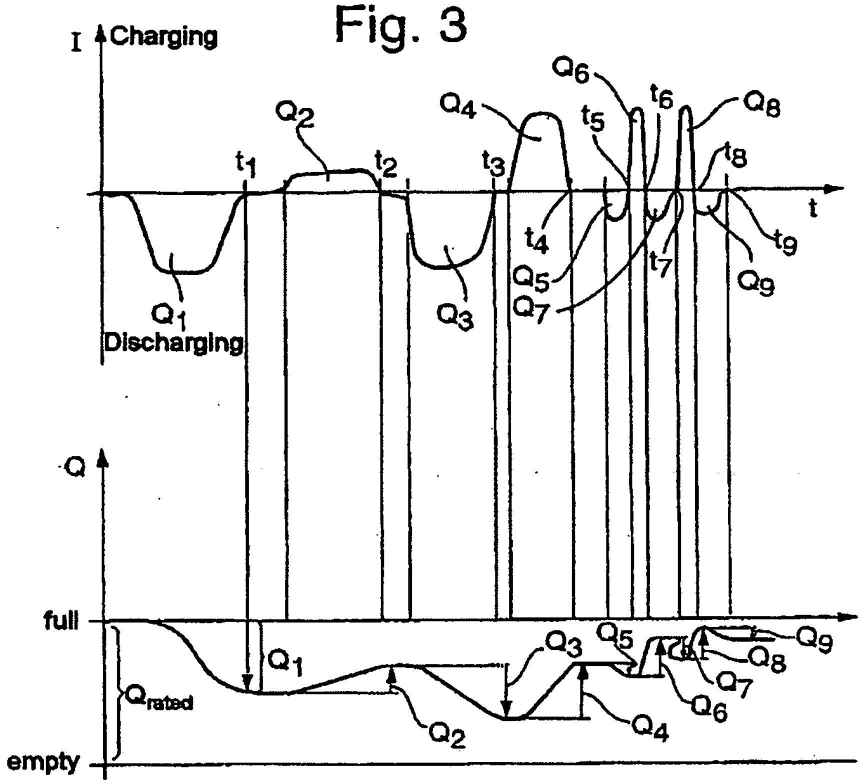


Fig. 2

Fig. 3


I
Charging
Discharging
Q2
Q4
Q6
Q8
t1
t2
t3
t4
t5
t6
t7
t8
t9
t
Q1
Q3
Q5
Q7
Q9
Q
full
Qrated
empty

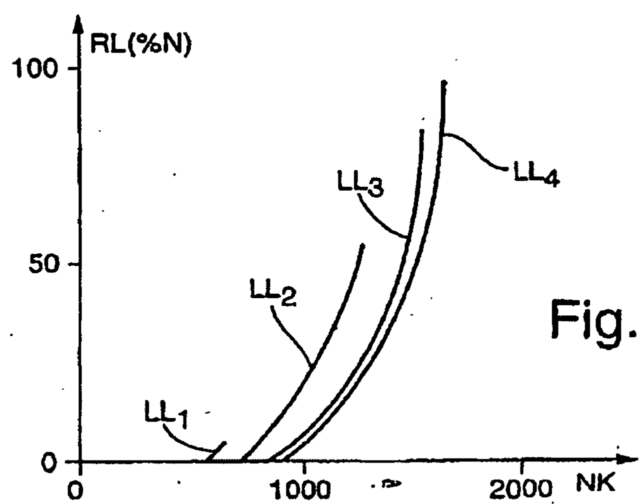
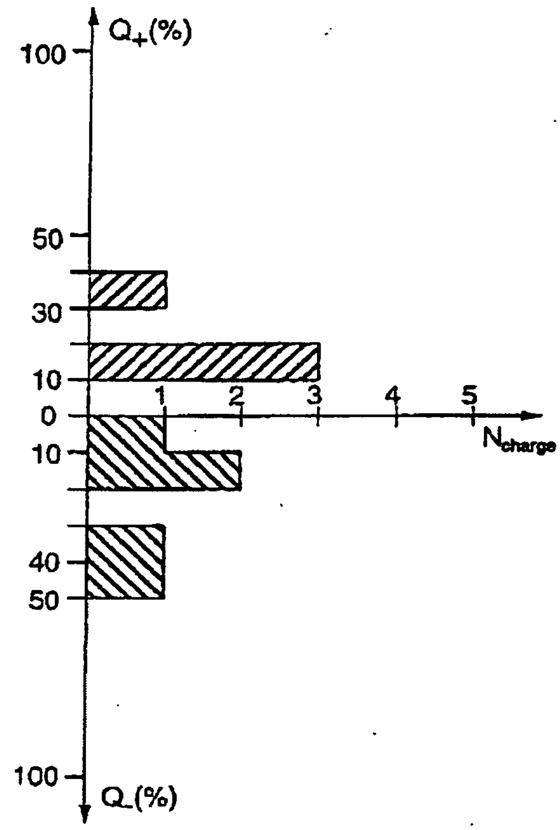

RL(%N)
100
50
0
0
1000
2000
NK
LL1
LL2
LL3
LL4

Fig. 7

Fig. 4


Q+(%)
100
50
30
10
0
10
40
50
100
Q-(%)
1
2
3
4
5
Ncharge

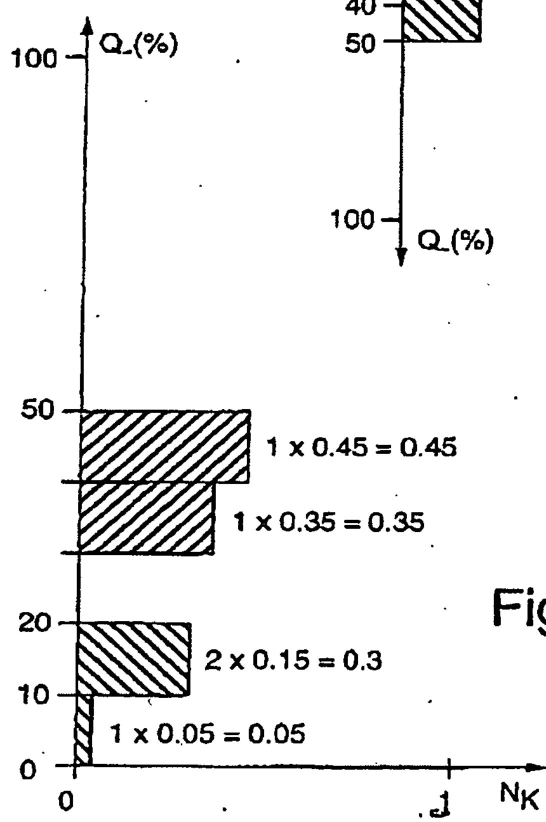
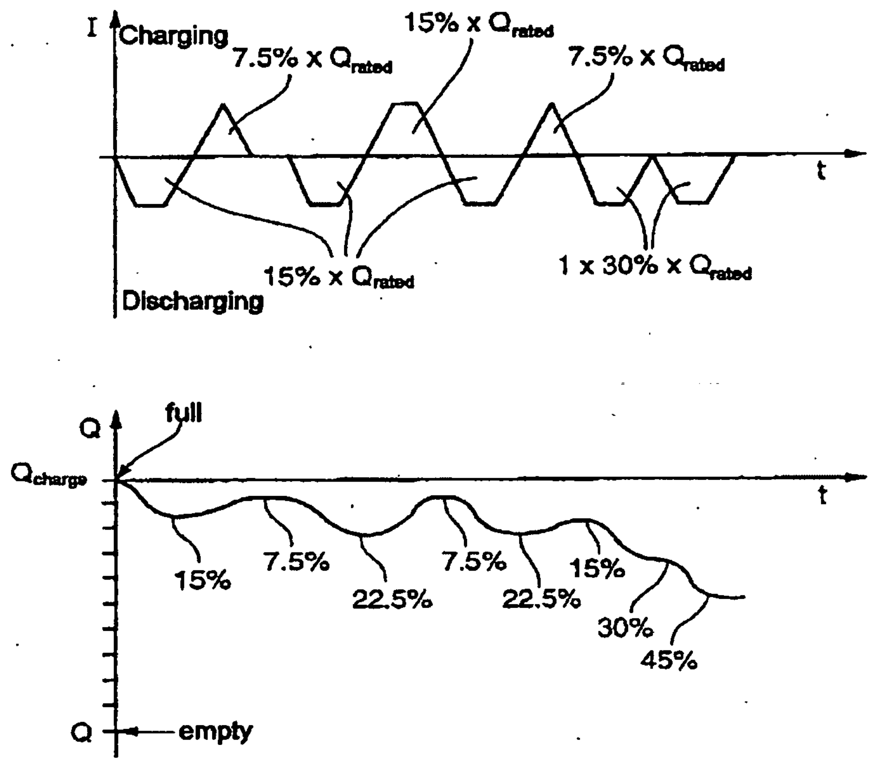

Q-(%)
100
50
20
10
0
1 x 0.45 = 0.45
1 x 0.35 = 0.35
2 x 0.15 = 0.3
1 x 0.05 = 0.05
0
1
NK

Fig. 5

Number: DE 195 40 827 A1
Int. Cl^6: H 01 M 10/42
Date of publication May 23, 1996

Fig. 6



i \ j	0-10%	10-20%	20-30%	30-40%	. . .	
0-10%						
10-20%		1	2			
20-30%						
30-40%						
40-50%				1		
.						
.						
.						

Fig. 8

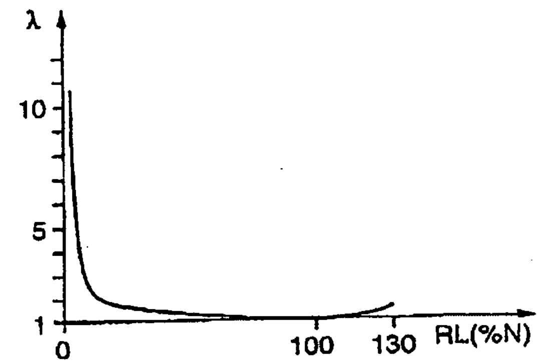


Fig. 9

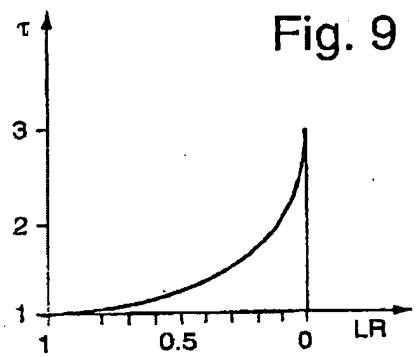


Fig. 10